

Edinburgh 2004/06
SHEP-04-08

An Interesting NMSSM Scenario at the LHC and LC: A Contribution to the LHC / LC Study Group

D.J. Miller¹ and S. Moretti²

¹ *School of Physics, The University of Edinburgh, Edinburgh EH93 JZ, Scotland*

² *School of Physics and Astronomy, The University of Southampton,
Highfield, Southampton SO17 1BJ, UK*

Abstract

The Next-to-Minimal Supersymmetric Standard Model NMSSM provides an attractive extension to the minimal supersymmetric model by including an extra Higgs singlet superfield. This extension allows one to link the Higgs-higgsino mass parameter μ to a vacuum expectation value of the new scalar field, thus providing a solution to the μ -problem of the MSSM. In this report, presented within the context of the LHC / LC Study Group, we examine a particularly interesting NMSSM scenario where the extra Higgs scalar is rather light. We determine LHC production cross-sections and branching ratios for the lightest scalar and find that it will be difficult to observe at the LHC. However, we show that this lightest scalar can instead be observed at an e^+e^- Linear Collider for all but a small window of parameter space.

1 Introduction

The Next-to-Minimal Supersymmetric Standard Model (NMSSM) provides an elegant solution to the μ problem of the MSSM by introducing an extra complex scalar Higgs superfield. The extra fields have no gauge couplings and are principally only manifest through their mixing with the other states. This leads to scenarios where Higgs boson couplings are reduced in comparison to the MSSM, presenting a challenge to the next generation of colliders. It is important that these extra Higgs states be seen in addition to the expected Higgs doublet states in order to distinguish the NMSSM from the MSSM. In this contribution, we will examine the phenomenology of one of these scenarios at the LHC and a future e^+e^- Linear Collider and demonstrate a synergy between the two machines.

The NMSSM has already been discussed in Section 2.4.1 of this study, in the context of establishing a “no-lose” theorem for the discovery of at least one Higgs boson at the next generation of colliders (see also Ref. [1]). It was seen that for some exceptional NMSSM parameter choices the discovery of *any* Higgs boson at all will be difficult at the LHC, but for the majority of choices at least one Higgs boson will be discovered. Here we adopt a different philosophy and examine a “typical” NMSSM scenario point. While not representative of scenarios over the entire range of parameters, the chosen scenario is certainly not unusual and a wide range of parameter choices will result in similar phenomenology, differing only in numerical detail and not in general structure. This scenario therefore presents an interesting illustrative picture of the Higgs sector that might be waiting to be explored in its full complexity at the next generation of colliders.

2 The Model

The NMSSM has the same field content as the minimal model augmented by an additional neutral singlet superfield \hat{S} . Its superpotential is given by

$$W = \hat{u}^c \mathbf{h}_u \hat{Q} \hat{H}_u - \hat{d}^c \mathbf{h}_d \hat{Q} \hat{H}_d - \hat{e}^c \mathbf{h}_e \hat{L} \hat{H}_d + \lambda \hat{S} (\hat{H}_u \hat{H}_d) + \frac{1}{3} \kappa \hat{S}^3, \quad (1)$$

where \hat{H}_u and \hat{H}_d are the usual Higgs doublet superfields with $\hat{H}_u \hat{H}_d \equiv \hat{H}_u^+ \hat{H}_d^- - \hat{H}_u^0 \hat{H}_d^0$. \hat{Q} and \hat{L} represent left handed quark and lepton weak isospin doublets respectively, while \hat{u}^c , \hat{d}^c and \hat{e}^c are the right handed quark and lepton fields; \mathbf{h}_u , \mathbf{h}_d and \mathbf{h}_e are matrices of Yukawa couplings where family indices have been suppressed. The usual μ -term of the MSSM, $\mu \hat{H}_u \hat{H}_d$, has been replaced by a term coupling the new singlet field to the usual Higgs doublets, $\lambda \hat{S} \hat{H}_u \hat{H}_d$. When the new singlet field gains a vacuum expectation value (VEV), an effective μ -term is generated with an effective Higgs-higgsino mass parameter given by $\mu_{\text{eff}} = \lambda \langle S \rangle$. (We adopt the notation that the superfields are denoted by expressions with a “hat”, while their scalar components are denoted by the same expression without the hat.) The superpotential resulting from this extension of the minimal model still contains an extra symmetry [before the kappa term in Eq.(1) is included] — a $U(1)$ “Peccei-Quinn” (PQ) symmetry [2], which will be broken when the singlet field gains a non-zero VEV. This spontaneous breaking results in a massless Nambu-Goldstone boson which is in this instance a pseudoscalar Higgs state. [In contrast the corresponding lightest scalar Higgs state is *not* massless.] Since this Higgs state has not been observed in experiment we have only two possibilities: we must either break the Peccei-Quinn

symmetry explicitly, giving the pseudoscalar a mass and putting it out of the kinematical reach of past experiments, or we must decouple it from the other particles by setting $\lambda \ll 1$. Here we adopt the former possibility¹, introducing an *explicit* Peccei-Quinn symmetry breaking term $\frac{1}{3}\kappa\hat{S}^3$. This results in the superpotential given in Eq.(1). We will not elaborate on the formal details of the model here except to elucidate our parameter choice — for a more detailed examination of the model see Ref. [4] and references therein.

At tree level, the NMSSM Higgs sector has seven parameters: the Higgs couplings from the superpotential, λ and κ ; their two associated soft supersymmetry breaking parameters, A_λ and A_κ ; and the VEVs of the three neutral Higgs fields, which we re-express as two ratios of VEVs, $\tan\beta = \langle H_u^0 \rangle / \langle H_d^0 \rangle$ and $\tan\beta_s = \sqrt{2}\langle S \rangle / v$, and the electroweak scale $v/\sqrt{2} = \sqrt{\langle H_u^0 \rangle^2 + \langle H_d^0 \rangle^2}$. The scenario to be considered here has parameters given by $\lambda = 0.3$, $\kappa = 0.1$, $\tan\beta = \tan\beta_s = 3$ and $A_\kappa = -60$ GeV. The parameter A_λ is replaced by the mass scale M_A which is chosen to be the diagonal entry of the pseudoscalar Higgs boson mass-squared matrix that returns to the value of the physical MSSM pseudoscalar Higgs boson mass in the MSSM limit (i.e. $\lambda \rightarrow 0$, $\kappa \rightarrow 0$ while keeping λ/κ and μ_{eff} fixed). This choice allows the reader a more intuitive connection with the MSSM. M_A will not be fixed, but will be allowed to vary over the physical range. Finally, we take $v = 246$ GeV.

3 The Mass Spectrum

The Higgs mass spectrum for our parameter choice, evaluated at one-loop precision [5], can be seen in Fig.(1), as a function of M_A . This spectrum looks remarkably like that of

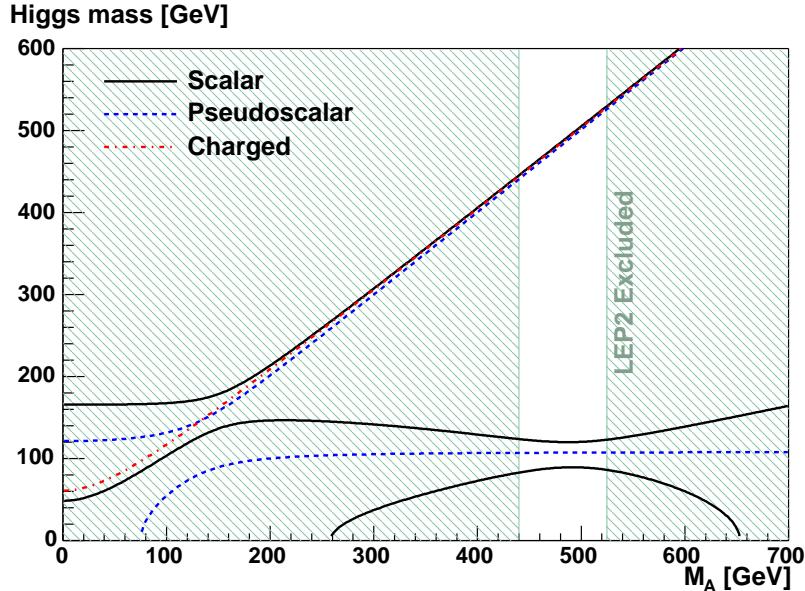


Figure 1: The one-loop Higgs mass spectrum as a function of M_A for $\lambda = 0.3$, $\kappa = 0.1$, $\tan\beta = \tan\beta_s = 3$ and $A_\kappa = -60$ GeV. Also shown by the shaded area are the values of M_A that are ruled out by LEP2 [6] for this parameter choice.

the MSSM with the addition of two extra Higgs fields — a scalar state and a pseudoscalar

¹For a description of the decoupled case, see Ref. [3].

state. As in the MSSM, the heavy pseudoscalar, scalar and charged Higgs bosons all lie around the mass scale M_A , while a lighter scalar state has mass around 115-130 GeV. However, in addition we see extra scalar and pseudoscalar states with masses of order 100 GeV and below; these are the Higgs states which are dominated by the extra singlet degrees of freedom.

Making an expansion in the (often) small parameters $1/\tan\beta$ and M_Z/M_A allows us to obtain simple approximate forms for the masses of these extra singlet dominated Higgs bosons [3]. One finds that the singlet dominated pseudoscalar Higgs fields has a mass given approximately by

$$M_{A_1}^2 \approx -\frac{3}{\sqrt{2}}\kappa v_s A_\kappa, \quad (2)$$

while the singlet dominated scalar has a mass which is maximized at $M_A \approx 2\mu_{\text{eff}}/\sin 2\beta$ where it is given by

$$M_{H_1}^2 \approx \frac{1}{2}\kappa v_s(4\kappa v_s + \sqrt{2}A_\kappa). \quad (3)$$

It must be stressed that these expressions are approximate and are not applicable over the entire parameter range; the one-loop expressions for the masses should be used in preference, as in Fig.(1). However, the approximate expressions are useful in determining the qualitative behaviour of the masses as the parameters are varied. [Although approximate, these expressions do surprisingly well in estimating the singlet dominated masses. For example, for the present parameter choice they give $M_{A_1} \approx 96.2$ GeV and $M_{H_1} \approx 88.1$ GeV, which compare favourably with the one-loop results, 107.3 GeV and 89.5 GeV respectively at $M_A = 495$ GeV. This is in part due to the suppression of couplings to quarks, which reduces the impact of radiative corrections.]

In particular, the masses are strongly dependent only on the quantities κv_s and A_κ [and M_A]. The dependence on κv_s (which is a measure of how strongly the PQ symmetry is broken) is straightforward: as κv_s increased the masses also increase. Since one expects v_s to be of the order of v and κ is restricted by $\kappa^2 + \lambda^2 \lesssim 0.5$ when one insists on perturbativity up to the unification scale, it is natural (though not mandatory) for this mass scale to be rather low, and the extra Higgs states rather light. In contrast, the A_κ contribution to the masses has opposite sign for scalar and pseudoscalar. The dependence of the pseudoscalar mass, Eq.(2), on A_κ indicates that A_κ should be negative, while Eq.(3) insists that its absolute value does not become too large. These effects are nicely summarized by the approximate mass sum rule (at $M_A \approx 2\mu_{\text{eff}}/\sin 2\beta$):

$$M_{H_1}^2 + \frac{1}{3}M_{A_1}^2 \approx 2(\kappa v_s)^2. \quad (4)$$

The overall scale for the masses is set by κv_s , while increasing the scalar mass leads to a decrease in the pseudoscalar mass and vice versa.

Fig.(1) also shows the values of M_A that, for this parameter choice, are already ruled out by LEP (the shaded region). Although a SM Higgs boson with mass below 114.4 GeV is now ruled out with 95% confidence by the LEP experiments [6], lighter Higgs bosons are still allowed if their coupling to the Z boson is reduced. In the NMSSM, since the extra singlet fields have no gauge couplings, the couplings of the singlet dominated fields to the Z boson come about only through mixing with the neutral doublet Higgs fields. When this mixing is small their couplings are reduced and they can escape the Higgs-strahlung dominated LEP limits. For the LEP limits shown here we take into account decays to both

$b\bar{b}$ [6] and $\gamma\gamma$ [7], as well as decay mode independent searches carried out by the OPAL detector [8]. As expected, the limits are dominated by the decay $H_1 \rightarrow b\bar{b}$.

The dependence of the lightest Higgs boson mass on M_A also makes a prediction for the mass of the heavy states. The lightest Higgs boson mass must be kept large enough to escape the current LEP limits. However, since this mass decreases rapidly to either side of its maximum (see Fig.(1) we are forced to constrain M_A , and thus the heavy Higgs boson masses, to around $M_A \approx 2\mu_{\text{eff}} / \sin 2\beta \approx \mu_{\text{eff}} \tan \beta$.

There is still significant room for a rather light Higgs bosons to be found the LHC and/or a LC. It is essential that these light Higgs bosons be ruled out or discovered at the next generation of colliders. In the following we will focus on the production of a light singlet dominated scalar Higgs boson at the LHC and a LC and its subsequent decay, but one should bear in mind that there is also a light pseudoscalar Higgs boson which also deserves study.

4 Branching ratios for the light scalar

The dominant branching ratios of the lightest scalar Higgs boson are shown in Fig.(2) as a

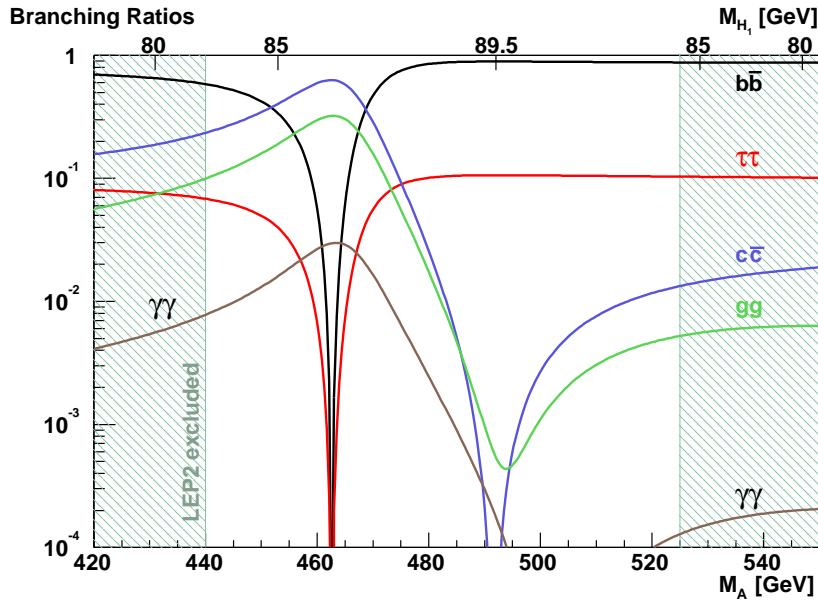


Figure 2: The dominant branching ratios for the lightest scalar Higgs boson as a function of M_A for $\lambda = 0.3$, $\kappa = 0.1$, $\tan \beta = \tan \beta_s = 3$ and $A_\kappa = -60$ GeV. The complicated structure is due to the switching off of the Higgs boson couplings to up-type and down-type quarks and leptons.

function of M_A . For a SM Higgs boson of the same mass (around 80 – 90 GeV) one would expect the dominant decays to be to bottom quarks, τ leptons, and charm quarks, with the addition of loop induced decays to gluons and photons. These are indeed also the dominant decays of the singlet dominated scalar for most of the allowed M_A range, but the branching ratios now show significant structure at approximately 463 GeV and again at around 490 GeV due to the suppression of various couplings.

The couplings of the lightest Higgs scalar to up-type and down-type quarks and leptons are given in terms of the SM Higgs couplings by

$$g_{H_1 u \bar{u}}^{\text{NMSSM}} = (O_{11}^H \cot \beta + O_{21}^H) g_{H u \bar{u}}^{\text{SM}}, \quad (5)$$

$$g_{H_1 d \bar{d}}^{\text{NMSSM}} = (-O_{11}^H \tan \beta + O_{21}^H) g_{H d \bar{d}}^{\text{SM}}, \quad (6)$$

respectively, where O_{11}^H and O_{21}^H are elements of the scalar Higgs mixing matrix. The relative minus sign between terms in Eq.(5) and Eq.(6) has the same origin as the relative minus sign between the $h u \bar{u}$ and $h d \bar{d}$ couplings in the MSSM.

The first structure seen in Fig.(2), at around 463 GeV, is due to the cancellation of $-O_{11}^H \tan \beta$ with O_{21}^H in Eq.(6), forcing the $H_1 \rightarrow b \bar{b}$ and $H_1 \rightarrow \tau^+ \tau^-$ branching ratios to vanish. As M_A is increased, O_{21}^H passes smoothly through zero, eventually canceling with $O_{11}^H \cot \beta$ in Eq.(5). This provides the structure at around 490 GeV where the $H_1 \rightarrow c \bar{c}$ branching ratio vanishes.

The decays to gg and $\gamma\gamma$ are mediated by loop diagrams giving a more complex behaviour. $H_1 \rightarrow gg$ is dominated by top and stop loops and consequently shows a marked decrease as the $H_1 t \bar{t}$ coupling switches off; although the top-loop contribution will pass through zero here, stop loops and bottom (s)quark loops prevent the branching ratio from vanishing. In addition to top and bottom (s)quark loops the $\gamma\gamma$ branching ratio is mediated by virtual W bosons, charged Higgs bosons and charginos. The dominant effect is from the W bosons and the top loops and so we see a broad suppression over the range where these couplings vanish.

5 LHC Production

Cross-sections for the production of the lightest scalar Higgs boson in various channels at the LHC are shown in Fig.(3). The total production cross-section is dominated by gluon-gluon fusion, and is sizable over the entire range. Other significant production channels are vector boson fusion ($VV \rightarrow H_1$), Higgs-strahlung ($W \rightarrow WH_1$ and $Z \rightarrow ZH_1$) and associated production together with top and bottom quarks ($gg \rightarrow H_1 t \bar{t}$ and $gg \rightarrow H_1 b \bar{b}$ respectively). As we saw for the branching ratios we again see structures which are associated with the couplings of the Higgs boson to various particles passing through zero. However, in contrast to the earlier discussion, there are now three, rather than two, significant values of M_A where structure appears. The coupling of the Higgs boson to a vector boson $V = W, Z$ with respect to the SM is given by

$$g_{H_1 VV}^{\text{NMSSM}} = O_{21}^H g_{H_1 VV}^{\text{SM}}, \quad (7)$$

where O_{21}^H is the same element appearing in Eqs.(5–6), so when this mixing element vanishes the vector boson fusion and Higgs-strahlung cross-sections will disappear. The H_1 state at this point is *not* a purely singlet state. The initial rotation of the doublet scalars by the angle β ensured that the only one of the doublet scalars has a coupling to vector bosons. The vanishing of the $H_1 VV$ coupling only requires that there be none of this doublet state mixed in with H_1 ; the H_1 field may (and does) still contain some of the doublet scalar which does not couple to the vector bosons. This M_A point where the $H_1 VV$ coupling vanishes is very close to the point where the $H_1 t \bar{t}$ coupling vanishes because the first term on the right-hand-side of Eq.(5) is suppressed by $1/\tan \beta$.

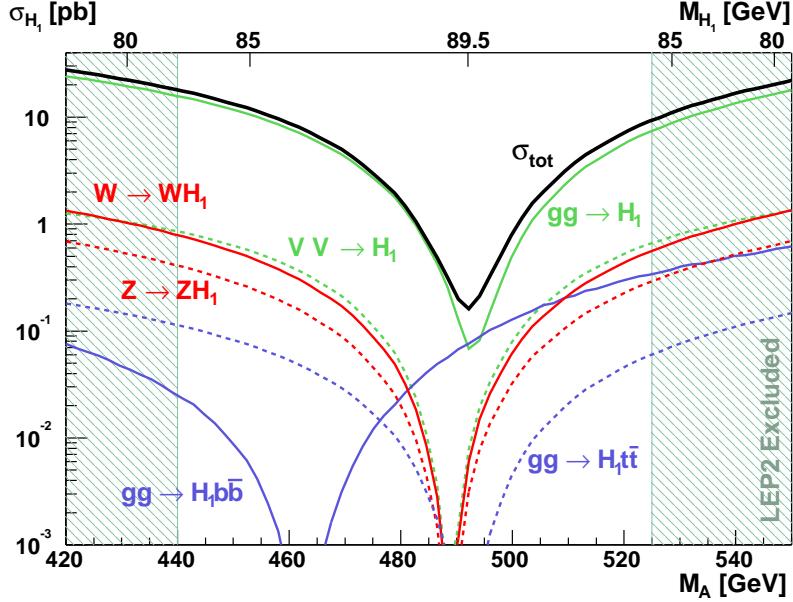


Figure 3: Production cross-sections for the lightest scalar Higgs boson at the LHC, as a function of M_A for $\lambda = 0.3$, $\kappa = 0.1$, $\tan \beta = \tan \beta_s = 3$ and $A_\kappa = -60$ GeV.

For the lower values of M_A , where the Higgs decay to $b\bar{b}$ is suppressed, this Higgs boson may be visible via its decay to $\gamma\gamma$ (with a branching ratio $\gtrsim 0.1\%$ for $M_A \lesssim 480$ GeV). However, as the $\gamma\gamma$ branching ratio is turned off at higher M_A , seeing this Higgs boson will become much more challenging. Although the cross-section remains relatively large, the Higgs boson almost always decays hadronically and the signal has a very large QCD background. The only significant non-hadronic decay is the Higgs decay to τ -pairs with a branching fraction of approximately 10%, but this also has large SM backgrounds.

The chosen scenario is extremely challenging for the LHC, but it is by no means a “worst-case scenario”. For example, increasing the value of $\tan \beta$ would increase the separation between the b -quark and vector boson switch-off points, moving the M_A range with an enhanced $H_1 \rightarrow \gamma\gamma$ branching ratio out of the allowed region. Alternatively, increasing the value of κv_s slightly would lead to a light Higgs boson sitting right on top of the Z -peak, making it very difficult to disentangle from the SM backgrounds. If the value of κv_s is significantly larger (and $|A_\kappa|$ not too large), the singlet dominated scalar would be heavy enough to decay to a vector boson pair, making its detection much easier. However, if the value of M_A is such that the coupling of Eq.(7) vanishes, these golden channels would be lost.

6 LC Production

The vanishing of the HVV couplings in the region of interest is particularly significant for a LC since the most promising production mechanisms are vector boson fusion, e.g. $e^+e^- \rightarrow W^+W^-\nu\bar{\nu} \rightarrow H_1\nu\bar{\nu}$, and Higgs-strahlung, $e^+e^- \rightarrow Z^* \rightarrow ZH_1$. The cross-sections for these processes at a $\sqrt{s} = 500$ GeV LC are plotted in Fig.(4) for our parameter choice, as a function of M_A , and show the distinctive vanishing of the H_1VV coupling. Never-

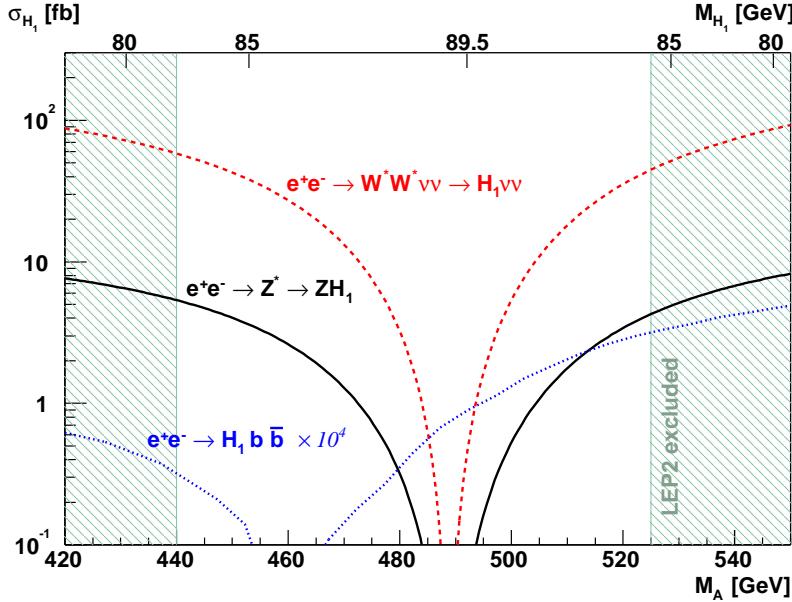


Figure 4: Production cross-sections for the lightest scalar Higgs boson at a $\sqrt{s} = 500$ GeV LC, as a function of M_A for $\lambda = 0.3$, $\kappa = 0.1$, $\tan \beta = \tan \beta_s = 3$ and $A_\kappa = -60$ GeV. The cross-section for $e^+e^- \rightarrow H_1 b\bar{b}$ has been multiplied by 10^4 .

theless, the lightest scalar Higgs boson would be seen by these channels for all of the M_A range except for a small window around 490 GeV. In contrast to the LHC, for most of the the observable region decays to $b\bar{b}$ and/or $\tau^+\tau^-$ could be easily used due the LC's relatively background free environment. For M_A values where the bottom and τ couplings vanish, the decays to $\gamma\gamma$ and charm may be used instead. Indeed, as long as the Higgs-strahlung cross sections are non-negligible, the associated Higgs particles can be discovered irrespective of the Higgs decay properties.

It is difficult to see what production mechanism could be used to close the remaining window around the critical point where the HVV couplings vanish. Higgs production in association with a top quark pair, $e^+e^- \rightarrow H_1 t\bar{t}$, is vanishingly small here because of the proximity of the $H_1 VV$ and $H_1 t\bar{t}$ "turning-off" points (they will move even closer as $\tan \beta$ is increased). The production in association with bottom quarks is shown in Fig.(4), multiplied by a factor of 10^4 to be visible on the same scale. Generally, this production process has three contributing sub-processes: Higgs-strahlung, $e^+e^- \rightarrow ZH_1$, followed by the Z decay to a bottom quark pair; Higgs pair production, $e^+e^- \rightarrow H_1 A_i$ ($i = 1, 2$) followed by the pseudoscalar decaying to bottom quarks; and bottom quark pair production, $e^+e^- \rightarrow b\bar{b}$ followed by the radiation of H_1 off a bottom quark. The first contribution is very closely related to the Higgs-strahlung already shown in Fig.(4) [simply multiplied by the $Z \rightarrow b\bar{b}$ branching ratio], so contains no new information and is *not* included in the $e^+e^- \rightarrow H_1 b\bar{b}$ cross-section shown. The second contribution is only kinematically allowed for the lightest pseudoscalar Higgs boson and is vanishingly small because two small mixings are needed (neither scalar nor pseudoscalar singlet fields have a Z coupling). Therefore the remaining process is dominated by Higgs radiation off bottom quarks, and although this switches off at a different M_A value, it is too small to be useful because of the small bottom quark Yukawa coupling.

At a LC with $\sqrt{s} = 800$ GeV, these cross-sections are modified as shown in Fig.(5). The

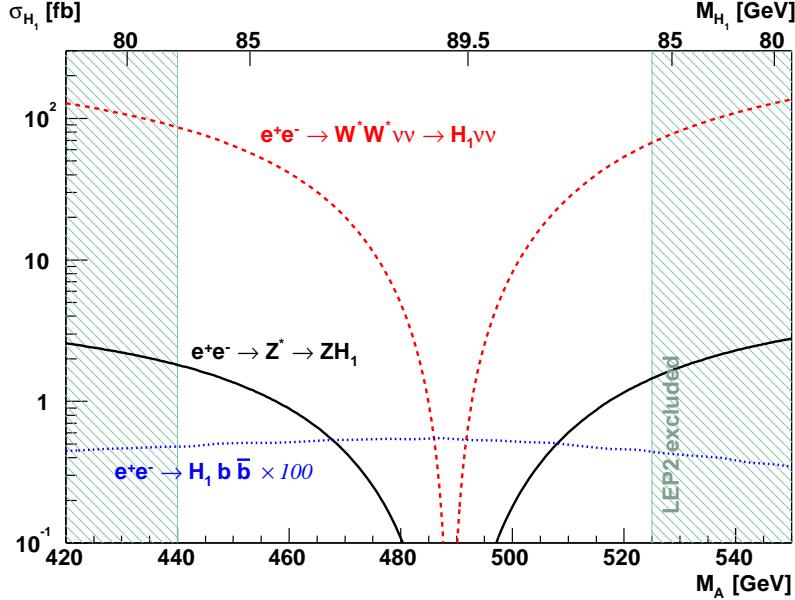


Figure 5: Production cross-sections for the lightest scalar Higgs boson at a $\sqrt{s} = 800$ GeV LC, as a function of M_A for $\lambda = 0.3$, $\kappa = 0.1$, $\tan \beta = \tan \beta_s = 3$ and $A_\kappa = -60$ GeV. The cross-section for $e^+e^- \rightarrow H_1 b\bar{b}$ has been multiplied by 100.

t-channel W -fusion cross-section increases, while the s -channel Higgs-strahlung cross-section decreases, but the overall M_A dependence remains the same, with both cross-sections vanishing at around 490 GeV. The $e^+e^- \rightarrow H_1 b\bar{b}$ associated production cross-section has increased dramatically due to the opening up of $e^+e^- \rightarrow H_1 A_2$, which was kinematically disallowed at $\sqrt{s} = 500$ GeV. Since this new contribution contains no $H_1 b\bar{b}$ coupling, the cross-section no longer vanishes at around 460 GeV, but unfortunately it is still too small to be of practical use².

Increasing κv_s and thus the singlet dominated masses only reduces the production cross-sections in line with the expectations of a reduced phase space. If the singlet dominated scalar is heavy enough, and M_A is far enough away from its critical value, the scalar will decay to vector bosons, making its discovery easier.

7 Conclusions

In this contribution we have considered a particularly challenging NMSSM scenario, presenting masses, branching ratios and production cross-sections at both the LHC and a future e^+e^- LC. Such scenarios have a Higgs spectrum very similar to the MSSM, i.e. nearly degenerate heavy charged, scalar and pseudoscalar states and a light Higgs boson at around 120–140 GeV, supplemented by an additional singlet dominated scalar and

²This cross-section has been calculated under the assumption of a fixed width (of 1 GeV) for A_2 , and is only intended to present an order of magnitude estimate.

pseudoscalar. We have seen that there is still room allowed by LEP for the singlet dominated Higgs boson to be very light, i.e. $\lesssim M_Z$. Despite having reasonably large production cross-sections at the LHC, this light Higgs boson would be difficult to see since its mainly hadronic decays cannot be easily untangled from the SM backgrounds. At a LC, this light scalar can be seen via vector boson fusion and Higgs-strahlung for most of the parameter range, except for a small region where the Higgs-vector boson coupling vanishes. The observation of this light scalar state at the LC, in addition to the light MSSM type scalar at the LHC, provides an unambiguous signal for an extended supersymmetric theory beyond the minimal version. If this Higgs boson is discovered at a LC but is missed at the LHC, LC input would be vital in providing information for trigger and background removal when the LHC endeavours to confirm the discovery.

We have also seen that a such a light Higgs boson may place restrictions on the masses of the heavier Higgs bosons. For small κv_s , in order to avoid detection of the light scalar at LEP, we require $M_A \approx \mu \tan \beta$. [The veracity of the pre-condition “small κv_s ” may be ascertained by also observing the singlet dominated pseudoscalar, by e.g. $e^+e^- \rightarrow t\bar{t}A_1$, and making use of the approximate sum rule of Eq.(4).] This prediction for the heavy Higgs boson masses would be invaluable to the LHC.

In this scenario the H_2 , H_3 and A_2 will be present, looking very much like the MSSM Higgs bosons h , H and A respectively with slightly altered couplings and could be detected in the usual way.

For heavier singlet dominated states, the position of the LHC is more favourable, since the clean decay to vector bosons opens up [although again, this is not useful over the entire M_A range]. Also the LHC’s kinematic reach will prove useful in discovering or ruling out very heavy singlet dominated Higgs states. On the other hand, if the extra singlet dominated Higgs boson is found to be almost degenerate with the lightest doublet dominated Higgs boson, LC precision may be required to disentangle the two states.

In summary, in order to provide complete coverage over the NMSSM parameter space, both the LHC and an e^+e^- LC will be needed. Not only can the LC probe areas where the LHC cannot, it can provide valuable input to the LHC investigation of the NMSSM Higgs sector.

Acknowledgments

DJM thanks the University of Southampton for their hospitality while part of this work was carried out.

References

- [1] U. Ellwanger, J. F. Gunion, C. Hugonie and S. Moretti, arXiv:hep-ph/0305109; arXiv:hep-ph/0401228 and this report.
- [2] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. **38** (1977) 1440; Phys. Rev. D **16** (1977) 1791.
- [3] D. J. Miller and R. Nevzorov, arXiv:hep-ph/0309143.
- [4] D. J. Miller, R. Nevzorov and P. M. Zerwas, arXiv:hep-ph/0304049.

- [5] P. A. Kovalenko, R. B. Nevzorov and K. A. Ter-Martirosian, Phys. Atom. Nucl. **61** (1998) 812 [Yad. Fiz. **61** (1998) 898].
- [6] R. Barate *et al.*, Phys. Lett. B **565** (2003) 61 [arXiv:hep-ex/0306033]; [LEP Higgs Working Group for Higgs boson searches Collaboration], arXiv:hep-ex/0107029.
- [7] Searches for Higgs Bosons Decaying into Photons: Combined Results from the LEP Experiments LHWG Note/2002-02, 12 July '02
- [8] G. Abbiendi *et al.* [OPAL Collaboration], Eur. Phys. J. C **27** (2003) 311 [arXiv:hep-ex/0206022].